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# COMPUTER OPTIMIZING OF BEVEL ANGLES
# WELDED PIPE JOINTS

BY

Professor H.W. Mergler

Case Institute of Technology

## ABSTRACT

The most common method for preparing the bevel-angle for welded pipe construction is to keep it at a constant value (say 37 degrees) around the entire periphery of the branch pipe. This paper explores the "optimized bevel-angle" as a function of pipe radii, wall thicknesses, centerline offset, and intersecting angle to keep the resulting weld cross section constant and thus minimize the weld volume while insuring' clearance for total weld penetration. The advantages of using the "optimized bevel angle" are demonstrated by computer simulation for pipe diameters from 4-l/2" to 24" for wall thicknesses over the range of 0.237" to 1.312". The ratio of the fixed bevel weld volume to the optimized bevel weld volume are shown to range from 1.5 to 5 which implies phenomenal reductions in the attendant welding time.

Computer Optimizing of Bevel Angles for Welded Pipe Joints

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Introduction - This paper is based on the following statements:

1. Pipe joint welding times are directly proportional to the applied weld volume.
2. To optimize (minimize) the joint weld volume requires the preparation of the mechanical joint such that the bevel angle f3 of the branch component be optimized along its periphery as a function of the outside radii of the joint components $R_m$ (main), and $R_b$ (branch), the wall thickness of the branch $T_b$, the angle of intersection of the joint components $\Theta$, the offset of the centerlines of the joint components $X_0$, two practical boundary limits on minimum and maximum values of B dictated respectively by the destructive burning of the joint lip and torch accessibility for total weld penetration and the independent variable $\phi$ defining the position along the periphery of the branch where the local value of B is defined. These parameters are shown in Figure 1.

The implied calculation in (2) above is straight-forward though formidable. This paper will discuss the computations necessary to de-. fine the locus for the branch saddle as a function of the above mentioned variables as well as of the determination of the optimized bevel angle.

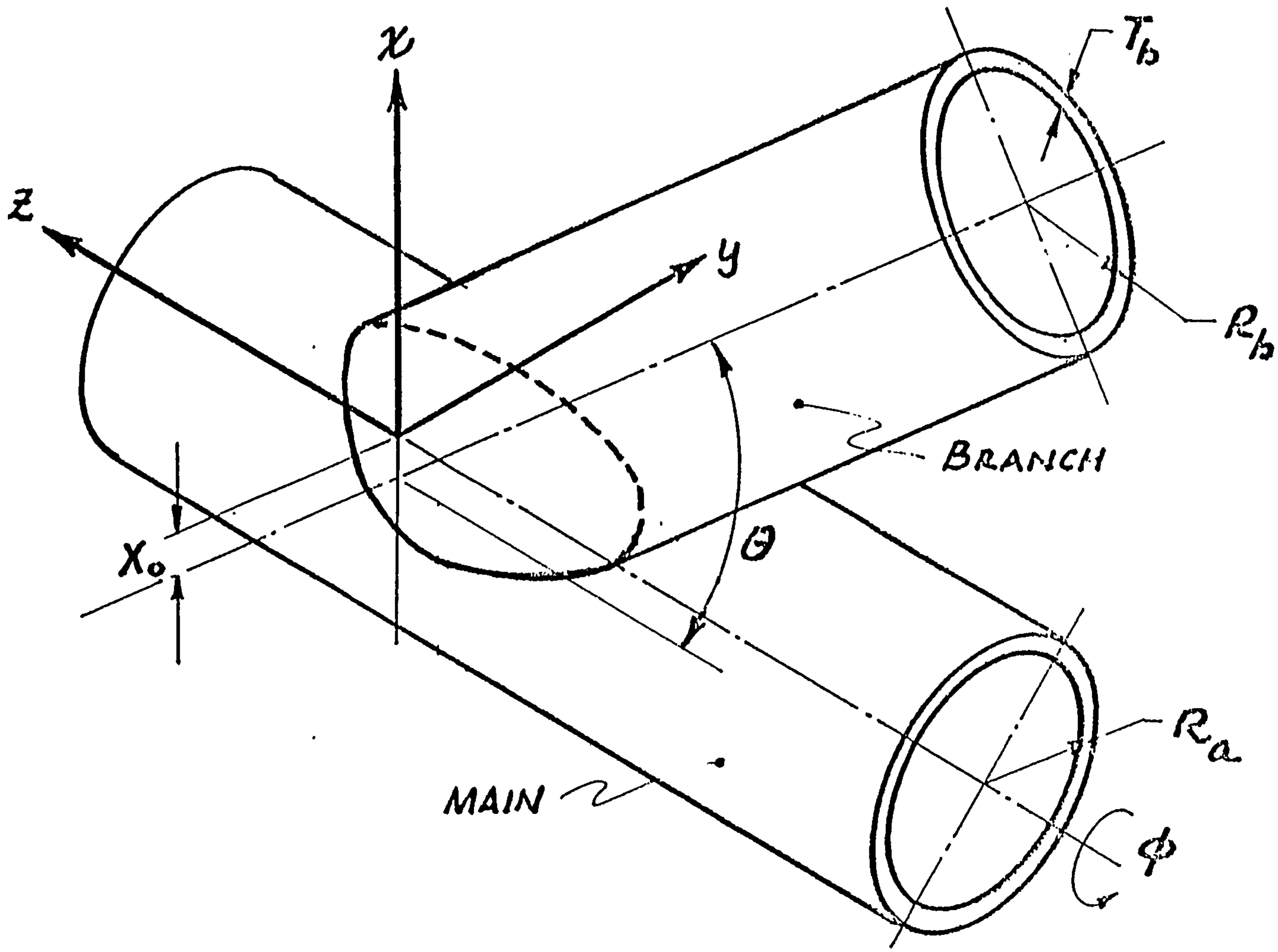



Figure 1. A Generalized Joint Configuration.

From these expressions the implied optimized weld volume may be determined and this weld volume will be shown to be dramatically smaller than those of pipe joints prepared with a constant bevel angle.

Symbols

| | | |
|---|---|---|
| x,y,Z | – | a reference coordinate frame |
| $Z_b$ | – | a linear cylindrical coordinate (a function of Ø) defining the branch saddle profile |
| $R_a$ | – | the outside radius of the main component |
| $R_b$ | – | the outside radius of the branch component |
| $T_b$ | – | the wall thickness of the branch component |
| $X_o$ | – | the center line offset between the main and the branch |
| $\theta$ | – | the angle between the main and the branch |
| $\phi$ | – | the angle in a plane perpendicular to the branch centerline defining a line on the branch parallel to its centerline |
| Y | – | the transformed coordinate ø |
| A | – | the transformed coordinate $X_\theta$ |
| $D_a$ | – | the outside diameter of the main component |
| $D_b$ | – | the outside diameter of the branch component |
| B | – | the bevel angle measured from the inner surface of the branch to the beveled surface |
| D | – | the weld preparation included angle |
| BEAN | – | the weld preparation angle being the complement of B |
| $L_1$ | – | the length of the weld section adjacent to the beveled surface |
| $L_2$ | – | the length of the weld section adjacent to the outer surface of the main component |
| $L_2$ | – | the modified length of $L_2$ |

$P_n$ - the area of the $n^{th}$ weld section

$P_M$ - the modified area of weld section

$V_C$ - the weld volume with B = constant

$V_o$ - the weld volume with B optimized

<u>Computing the Space Trajectory (Locus) of the Intersection of Two Pines - The</u> preparation of the mechanical joint of a main-branch pair may be thought of as three processes, the first two of which are done <u>concurrently</u>. They are

1. Preparation of the intersection profile on the branch
2. Preparation of the bevel angle along the profile of (1) above
3. Preparation of the saddle hole in the main

To develop the intersection locus (1) above consider a pipe joint with the following orientations shown in Figure 1.

1. The <u>main</u> component's centerline is coincident with the z axis and of radius $R_a$,
2. The <u>branch</u> component's centerline is parallel to the x-z plane and of radius $R_b$,
3. $X_0$ is the offset and is the x intercept of the branch's centerline on the X axis.
4. $\theta$ is the angle between the branch centerline and the x-z plane.
5. $\phi$ is independent variable measured around the z axis.

The resulting equation of the intersecting locus defined on the surface of the main component and expressed as a function of $\phi$ for fixed values of $R_a$, $R_b$, $\theta$, and $X_0$ is

$$Z(\phi) = R_a \cot\theta \sin\phi \pm |\csc\theta| \sqrt{R_b^2 - (R_a \cos\phi - X_0)^2} \quad (1)$$

Through coordinate translation the locus may be expressed in terms of the branch component as

$$z_b = R_b \cot(-\theta) \sin\phi \pm |\csc(-\theta)| \sqrt{R_a^2 - (R_b \cos\phi + X_o)^2} \qquad (2)$$

This (2) is the equation which describes the shape of the end of the branch for <u>proper</u> mechanical <u>profile</u> preparation of the joint. <u>It does not, however, address the nature of the bevel angle associated with this profile</u>.

<u>Computation of the Weld Cross Sectional Area</u> - The thrust of this paper is not the space trajectory of the intersecting surfaces as given by equations (1) and (2) but rather the determination of how to adjust the bevel angle on this trajectory to minimize the total weld volume.

Following a somewhat complex transformation[2] of coordinates and an integration over the range set by $R_a$ and the wall thickness $T_b$ a general expression for the weld area P may be derived as a function of y (the cylindrical angular coordinate around the z axis which is the axis of the branch component.

$$= \frac{T_b^2}{2}\cot\beta - \frac{T_b^2 \cos\gamma}{2\tan\theta} + \frac{T_b \cdot \sqrt{R_a^2 - [(R_b - T_b)\sin\gamma + A]^2}}{2\sin\theta}$$

$$+ \frac{(R_b \sin\gamma + A)}{2\sin\theta\sin\alpha}\left\{\sqrt{R_a^2 - [(R_b - T_b)\sin\gamma + A]^2} - \sqrt{R_a^2 - (R_b\sin\gamma + A)^2}\right\}$$

$$+ \frac{R_a^2}{2\sin\theta\sin\gamma}\left\{\sin^{-1}\left(\frac{R_b\sin\gamma + A}{-R_a}\right) - \sin^{-1}\left[\frac{(R_b - T_b)\sin\gamma + A}{-R_a}\right]\right\} \qquad (3)$$

Here A is the transformed offset $X_0$ in the original joint description.

Equation (3) is derived using a weld area bounded by the bevel surface of the branch, the surface of the main, and an extension of the outer surface of the branch to the main. A proper weld however strives to have both weld surfaces $L_1$ and $L_2$ be the same length. If $L_2 < L_1$' a point N Figure 2 will be moved to N' so that the length $L_2$ of N'I is equal to $L_1$. Figure 3 shows the general profile where $L_2 < L_1$. The point N is moved to a new position N' $(y_1, z_1)$ on the ellipse so that $L_2$ of N'I is equal to $L_1$. The modified weld area $P_M$ may be computed by making the following.substitutions in equation (3)'

$$T_b = T_{b'} = |Y_1 - y_o| \qquad (4)$$

$$R_b = R'_{b'} = |Y_1|$$

Yielding a weld area P'. The area F of the triangle M'MN must then be subtracted from P' to get the new modified weld area with equal legs i.e. $L_1 = L_2'$.

Thus $$F(B) = 1/_2(T'_b - T_b) \quad (T_b' \cot B + (Z_o - z_1)] \qquad (5)$$

and $$P_M = P' - F \qquad (6)$$

The Bevel Angle and Weld Preparation Angle - Equation (3) may be rewritten to express the bevel angle as a function of $R_b$' $T_b$' A, o, P and the independent variable y as

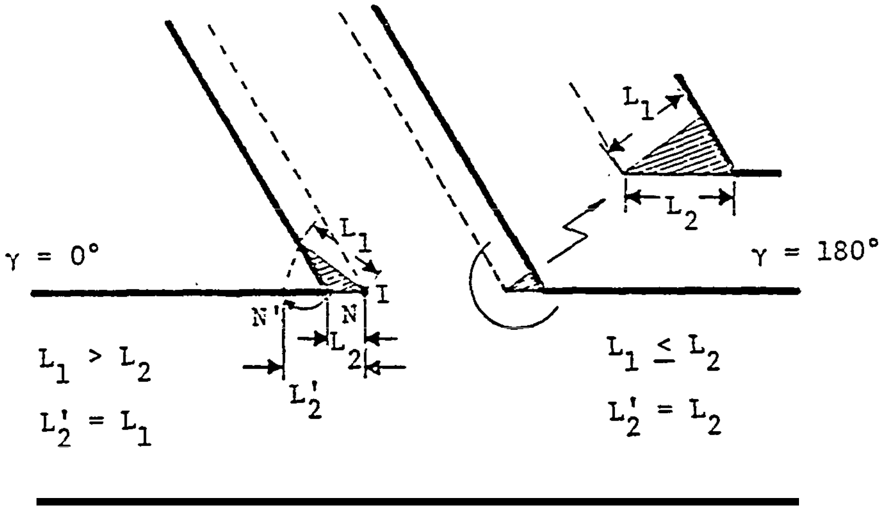



Figure 2. Modified Weld Areas in Pipe Joints for $6 \# 90^{\circ}$, and $y = 0^{\circ}, 180^{\circ}$.

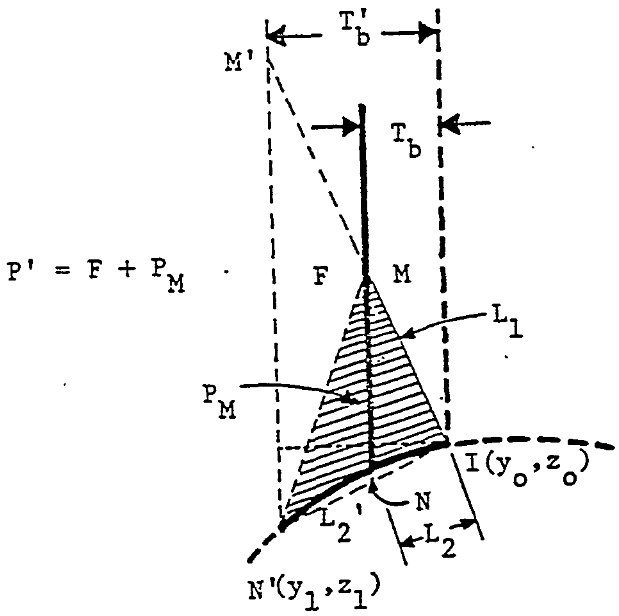



Figure 3. Intersection of the Modified Weld Area $P_N$ in a General Profile for $L_2 < L_1$.

$$B = \cot^{-1}\Big( \frac{2P}{T_b^2} + \frac{\cos y}{\tan 0} - \frac{\sqrt{R_a^2 - [(R_b - T_b)\sin y + A]^2}}{T_b \sin 9}$$

$$- \frac{1}{T_b^2 \sin 9 \ \sin y} \Big[ (R_b \sin y + A)\{\sqrt{R_a^2 - [(Rb-Tb)\sin y + A]^2}$$

$$- \sqrt{R_a^2 - (R_b \sin y + A)^2}\} + R_a^2 \Big(\sin^{-1}\Big(\frac{R_b \sin y + A}{R_a}\Big)$$

$$-\sin^{-1}\Big[\frac{(R_b - T_b)\ \sin Y + A}{R_a}\Big]\Big)\Big]\Big) \qquad (7)$$

Figure 4 shows this bevel angle 3 at two points on a typical branch. Of practical interest here are the limits placed on this angle. We designate the weld preparation angle as BEAN (the complement of B) as the angle of torch bevel measured from a line perpendicular to the surface of the branch pipe such that the wall will not be distorted by the torch heat. Experience indicates this should be no greater than 55° for plasma and 68° for.oxyacetelene. This maximum angle is designated DI in Figure 5. The-minimum angle (TI) of 37° (Figure 6) has been found to be the minimum angle to allow torch access to the joint to permit 100% weld penetration.

With these practical boundaries on the weld preparation angle we can compute the optimized weld volume ($V_o$) implied by the variable and optimized bevel angle and the fixed joint parameters $R_a$, $R_b$, $T_b$, 9, A around the branch-profile (expressed in the angle y).

The Weld Volume - From equation 3, which gives the localized weld area

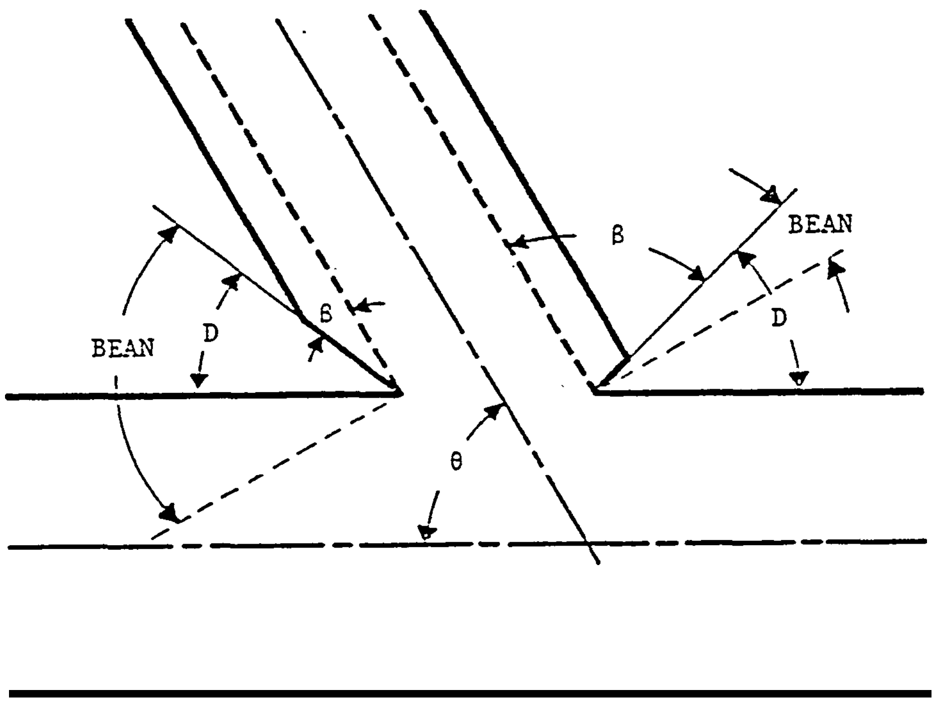



Figure 4. Interpretation of Bevel Angles BEAN, B Angles, and Weld Preparation Included Angles D.

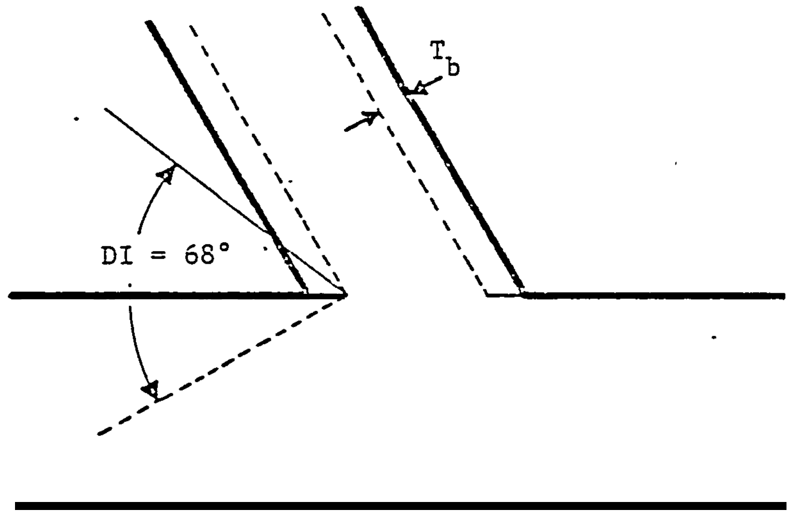



Figure 5. Maximum Allowable Bevel Angle DI in a Welded Pipe Joint.

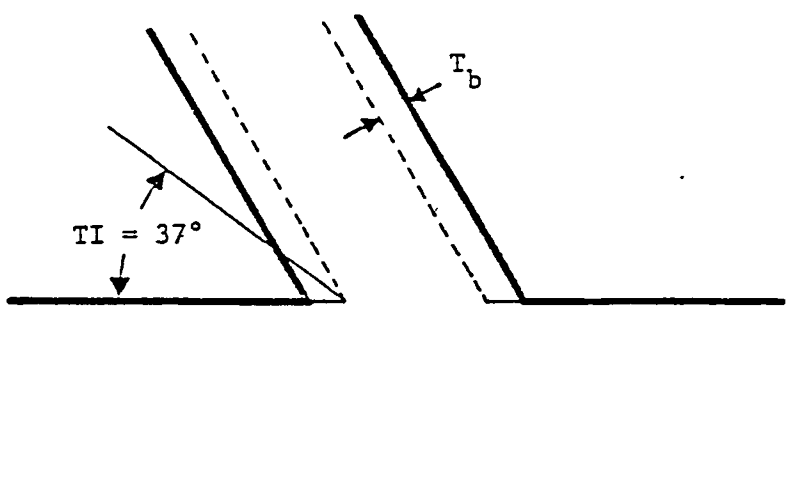



Figure 6. Minimum Allowable Weld Preparation Included Angle TI in a Welded Pipe Joint.

we may use numerical integration to compute the weld volume by the equation

$$\text{weld volume WEV} = \sum_{n=1}^{P} \frac{G\pi}{180} R_M P_n \tag{8}$$

where $n=1, 2 \ . \ . \ . \frac{360}{G}$

G = sample interval of y in degrees and $R_M = R_b + 1/3\ (T_B - 2T_b)$

Weld Volume for a Fixed Bevel Angle - Figure 7 - The weld volume may be readily calculated with equation (8) using a constant value for B in equation (3). Here $P_n$ is calculated for a constant B which is in turn dictated by the minimum weld preparation angle BEAN permitting 100 weld preparation. Here, (BEAN)CONSTANT is computed as

$$(\text{BEAN})_{\text{CONSTANT}} = D - (\text{TA})_{\text{MINIMUM}} \tag{9}$$

where D = say 37°

and $TA_{\text{MINIMUM}}$ = Minimum tangent angle which is the angle between a perpendicular to the interior wall of the branch and a line tangent to the main where the main is tangent to the branch interior wall.

Weld Volume for an Optimized Bevel - Figure 8 - Here we must first determine all tangent angles around the circumference of the branch. Then each optimized weld preparation angle $(\text{BEAN})_n$ equals the included angle D minus the local tangent angle $(\text{TA})_n$.

i.e. $$(\text{BEAN})_n = D - (\text{TA})_n \text{ where } n = 1,2,\ldots.. \frac{360}{G} \tag{10}$$

Thus, as the tangent angle changes, the corresponding bevel angle changes

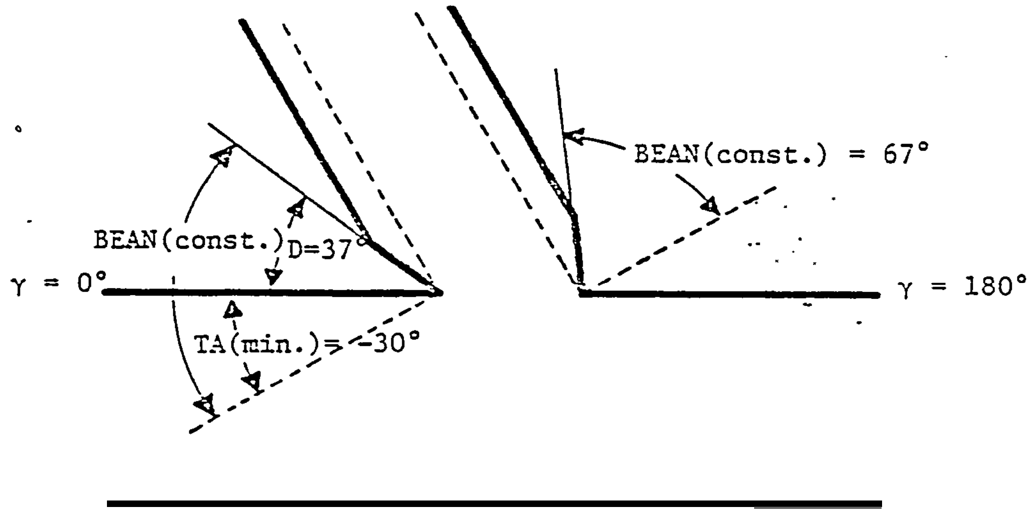



Figure 7. Profile of the Pipe Joints with Fixed Bevel Angle.

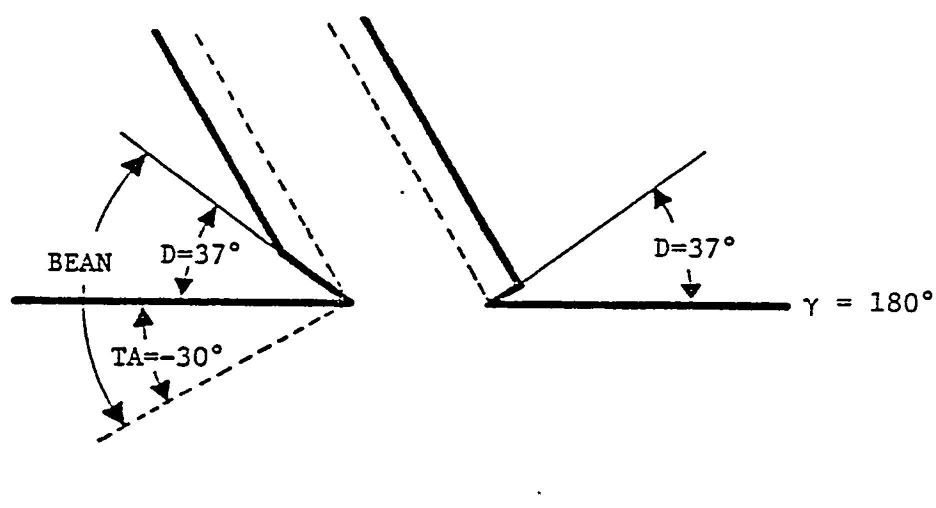


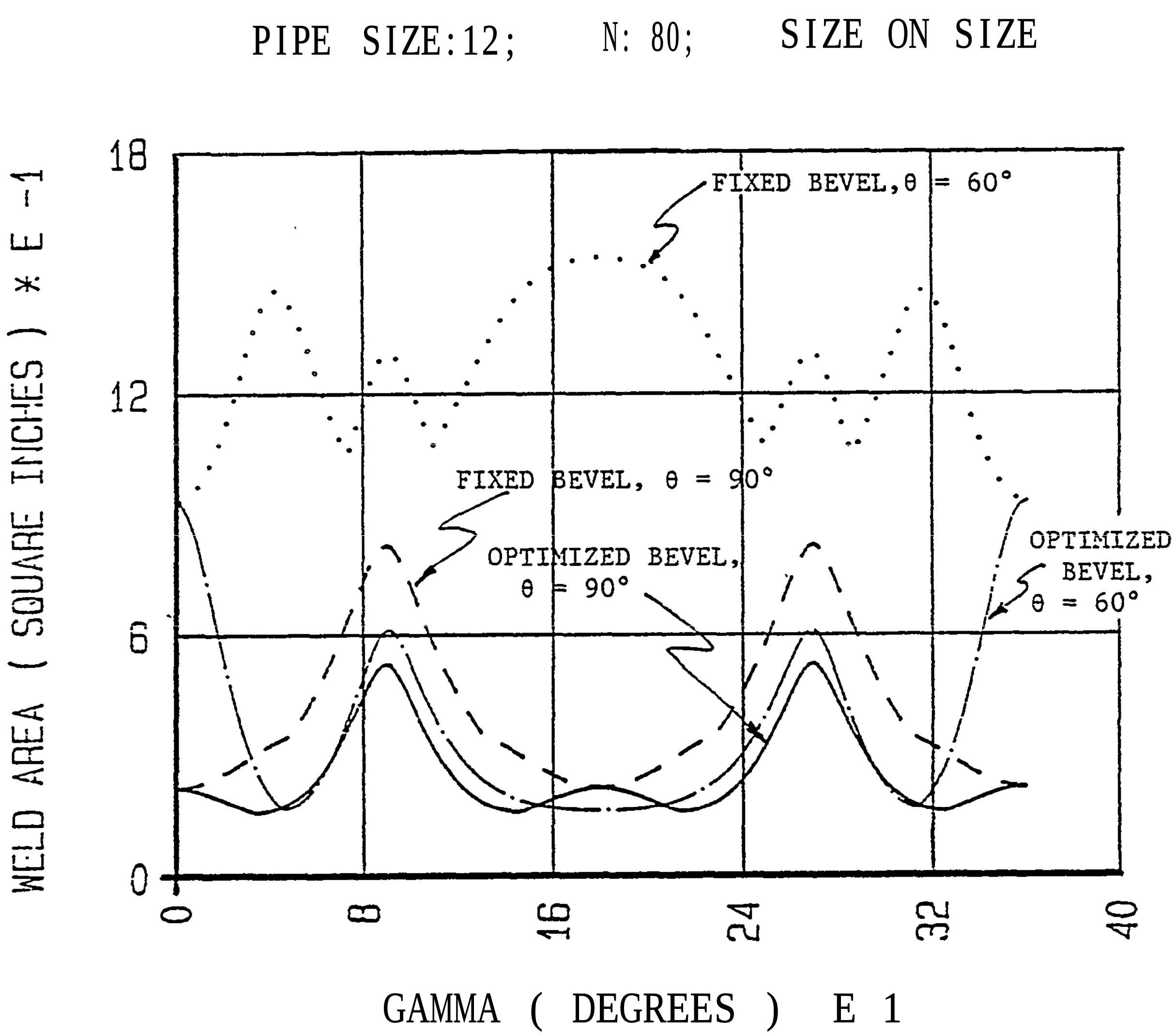

Figure 8. Profile of the Pipe Joints with Optimized Bevel Angle.

Table I - Weld Volume Comparison for Selected Joint Sizes and Configurations

| $D_a$ INCHES | Sched$_a$ | $D_b$ INCHES | Sched$_b$ | $T_b$ INCHES | $\theta$ DEGREES | $V_C$ IN$^3$ | V Q3 IS |
|---|---|---|---|---|---|---|---|
| 4.5 | 40 | 4.5 | 40 | .237 | 90 | .681 | .420 |
| | 40 | | 40 | .237 | 60 | 2.124 | .597 |
| | 80 | | 80 | .337 | 90 | 1.275 | .789 |
| | 80 | | 80 | .337 | 60 | 4.184 | 1.142 |
| | 120 | | 120 | .438 | 90 | 2.023 | 1.262 |
| | 120 | | 120 | .438 | 60 | 6.915 | 1.859 |
| | 160 | | 160 | .531 | 90 | 2.828 | 1.784 |
| | 160 | | 160 | .531 | 60 | 9.975 | 2.667 |
| | DBL.E.H. | | DBL.E.H. | .674 | 90 | 4.255 | 2.742 |
| | DBL.E.H. | | DBL.E.H. | .674 | 60 | 15.614 | 4.192 |
| 6.625 | STD.40 | 6.625 | STD.40 | .280 | 90 | 1.461 | 0.093 |
| | STD.40 | | STD.40 | .280 | 60 | 4.431 | 1.272 |
| | 80 | | 80 | .432 | 90 | 3.182 | 1.964 |
| | 80 | | 80 | .432 | 60 | 10.229 | 2.823 |
| | 120 | | 120 | .562 | 60 | 5.072 | 3.147 |
| | 120 | | 120 | .562 | 90 | 16.958 | 4.592 , |
| | 160 | | 160 | .719 | 60 | 7.805 | 4.897 |
| | 160 | | 160 | .719 | 90 | 27.154 | 7.271 |
| | DBL.E.H. | | DBL.E.H. | .864 | 60 | 10.719 | 6.817 |
| | DBL.E.H. | | DBL.E.H. | .864 | 90 | 38.451 | 10.279 |
| 8.625 | STD.40 | 8.625 | STD.40 | ,322 | 90 | 2.575 | 1.596 |
| | STD.40 | | STD.40 | .322 | 60 | 7.693 | 2.237 |
| | 80 | | 80 | .500 | 90 | 5.691 | 3.510 |
| | 80 | | 80 | .500 | 60 | 17.992 | 5.015 |
| | 120 | | 120 | .719 | 90 | 10.853 | 6.730 |
| | 120 | | 120 | .719 | 60 | 36.118 | 9.810 |
| | 160 | | 160 | .906 | 90 | 16.272 | 10.191 |
| | 160 | | 160 | .906 | 60 | 56.307 | 15.093 |
| | DBL.E.H. | | DBL.E.H. | .875 | 90 | 15.314 | 9.572 |
| | DBL.E.H. | | DBL.E.H. | .875 | 60 | 52.690 | 14.141 |

| $D_a$ INCHES | $Sched_a$ | $D_b$ INTCHES | $Sched_b$ | $T_b$ INCHES | θ DEGREES | $V_C$ IN$^3$ | $V_{03}$ 13 |
|---|---|---|---|---|---|---|---|
| 12.750 | STD | 12.750 | STD | .375 | 90 | 5.391 | 3.362 |
| | STD | | STD | .375 | 60 | 15.669 | 4.671 |
| | 40 | | 40 | .406 | 90 | 6.231 | 3.876 |
| | 40 | | 40 | .406 | 60 | 18.272 | 5.401 |
| | 60 | | 60 | .562 | 90 | 11.235 | 6.941 |
| | 60 | | 60 | -562 | 60 | 34.254 | 9.797 |
| | 80 | | 80 | .688 | 90 | 16.169 | 9.972 |
| | 80 | | 80 | ,688 | 60 | 50.616 | 14.201 |
| | 120 | | 120 | 1.000 | 90 | 31.481 | 19.487 |
| | 120 | | 120 | 1.000 | 60 | 103.994 | 28.303 |
| | 160 | | 160 | 1.312 | 90 | 50.712 | 31.723 |
| | 160 | | 160 | 1.312 | 60 | 174.886 | 46.911 |
| | DBL.E.H. | | DBL.E.H. | 1.000 | 90 | 31.481 | 19.487 |
| | DBL.EeH. | | DBL.E.H. | 1.000 | 60 | 103.994 | 28.303 |
| 16. | 80 | 16. | 80 | .844 | 90 | 30.678 | 18.921 |
| | 80 | | 80 | .844 | 60 | 95.744 | 26.917 |
| | 160 | | 160 | 1.594 | 90 | 94.713 | 59.151 |
| | 160 | | 160 | 1.594 | 60 | 324.915 | 87.264 |
| 20. | 80 | 20. | 80 | 1.031 | 90 | 57.493 | 35.464 |
| | 80 | | 80 | 1.031 | 60 | 178.880 | 50.397 |
| | 160 | | 160 | 1.969 | 90 | 181.190 | 113.093 |
| | 160 | | 160 | 1.969 | 60 | 620.392 | 166.703 |
| 24. | 80 | 24. | 80 | 1.219 | 90 | 96.737 | 59.676 |
| | 80 | | 80 | 1.219 | 60 | 300.392 | 84.747 |
| | 160 | | 160 | 2.344 | 90 | 308.753 | 192.642 |
| | 160 | | 160 | 2.344 | 60 | 1055.813 | 283.798 |
| 8.625 | 80 | 4.5 | 80 | .337 | 90 | .921 | .600 |
| 8.625 | 80 | 4.5 | 80 | -337 | 60 | 4.737 | .975 |

| $D_a$ INCHES | Sched$_a$ | $D_b$ INCHES | Sched$_b$ | $T_b$ INCHES | $\theta$ DEGREES | $V_C$ IN$^3$ | $V_O$ IN$^3$ |
|---|---|---|---|---|---|---|---|
| 12.750 | 80 | 6.625 | 80 | ,432 | 90 | 2.245 | 1.455 |
| 12.750 | 80 | 6.625 | 80 | .432 | 60 | 11.473 | 2.354 |
| 16 | 80 | 8.625 | 80 | .500 | 90 | 3.964 | 2.542 |
| 16 | 80 | 8.625 | 80 | .500 | 60 | 19.996 | 4.067 |




The Weld Areas around the Branch Pipe Circumference
for DA = DB = 12.75 in. and TB = 0.688 in.

accordingly, while the <u>weld preparation included angle</u> D remains constant.

The implied local optimized bevel angle derived from equation (10) is then used in equations (3) and (8) to give the <u>optimized weld volume</u>.

<u>Conclusions</u> - FORTRAN computer programs have been written to execute all computations implied by the preceding discussion. One hundred and twenty different joint configurations were studied for weld area variations for both fixed and optimized bevel angle configuration The studied cases included size on size and differing diameters, intersecting angles of 60° and 90°, offsets, pipe sizes from 4 inches to 24 inches and schedules from 40 to 160.

All cases studied showed a dramatic reduction in weld volume when the optimized volume ($V_o$) was compared to that ($V_c$) obtained using a fixed bevel angle. The results of this weld volume comparison are shown in Table I.

The results of this comparison are so dramatic that modification of current yard practice in the mechanical preparation of welded pipe joints must be given consideration. Existing pipe fabrication machinery may be realistically modified to permit this optimization and cost recoveries achieved using fabricated joints vs. the use of prefabricated couplings can be demonstrated to be rapid and persuasive.

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